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DRYING PROCEDURES FOR BACTERIALLY INFECTED NORTHERN RED OAK LUM--ETC(U)

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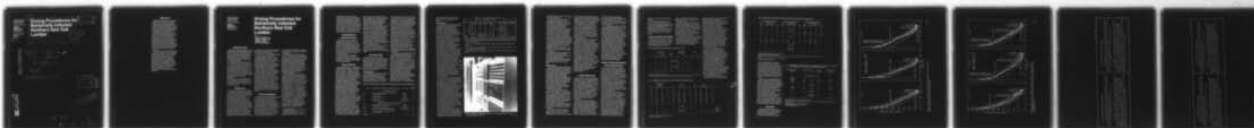
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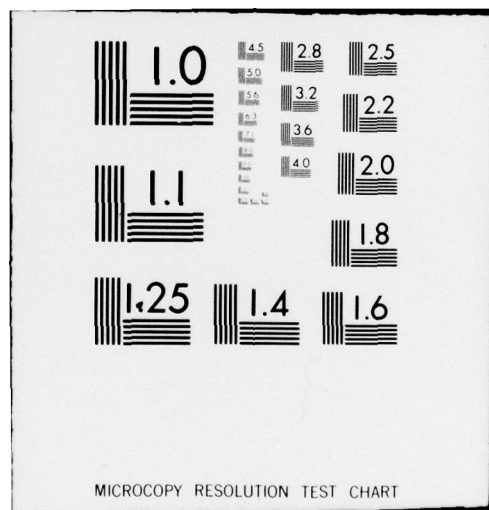


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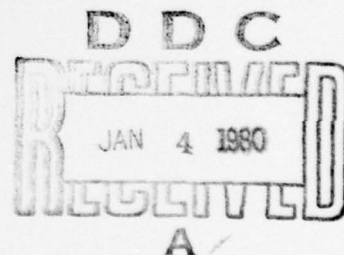
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## **ABSTRACT**

A series of tests were conducted to determine an optimum procedure for drying green 4/4 northern red oak lumber containing bacterially infected heartwood. This type of lumber is more likely to develop serious honeycomb, surface checks, and ring failure during kiln drying under normally mild schedules than is green lumber with normal, noninfected heartwood. First, bacterially infected lumber should be dried green from the saw by a low-temperature, forced-air schedule to at least 25 percent moisture content and preferably 20 percent. The forced-air dried lumber can then be kiln dried to 6 to 8 percent moisture content with good results by using a milder kiln schedule than normally recommended for air-dried oak.

Honeycomb will be eliminated except in boards with advanced, rancid stages of bacterial infection, but even these boards will have minimal honeycomb. Severe surface checking was not reduced as effectively in bacterially infected oak as was honeycombing. Ring failure was not greatly minimized because it is an incipient form of ring shake that begins in the living tree. For all tests in this study, shrinkage was greater for bacterially infected heartwood than for normal noninfected heartwood.



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# Drying Procedures for Bacterially Infected Northern Red Oak Lumber

By  
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## INTRODUCTION

Bacterially infected heartwood of oak presents special drying problems when the wood is to be kiln-dried green from the saw. Infected oak is more prone to develop honeycomb and ring failure than healthy oak, even though dried under conventional or normally "safe" kiln schedules (16, 18)<sup>2</sup>.

Kiln schedule T4-D2, recommended by the Forest Products Laboratory for 4/4-inch-thick red oak (13), was found in one study to be safe for green lumber with healthy heartwood, but not for infected lumber (18). Healthy oak could be dried faster under a schedule more severe than T4-D2 without honeycomb and ring failure, but the severity of these defects increased in bacterial heartwood.

This paper gives the results of more recent research to derive satisfactory procedures for drying infected 4/4 red oak under conditions milder than kiln schedule T4-D2.

## Background

This research followed principles of kiln schedule development in response to drying strain outlined by McMillen (9) whereby three factors affecting drying stresses must be considered: Temperature, relative humidity, and time. Successful development of a schedule depends upon determining the optimum combination of the three factors during drying lumber from green to final moisture content (MC). Surface and end checking, honeycombing, and ring failure result from shrinkage stresses caused by drying wood below the fiber saturation point. Prolonged exposure to excessive temperature while any of the wood is above the fiber

saturation point weakens the wood and increases its susceptibility to interior checking and collapse.

Until recently, it was generally felt that the ability of wood to withstand shrinkage stresses without rupturing depended largely on its MC, drying temperatures, rate of moisture loss, and the combined effect of time and temperature on reduction of strength. Now it appears that the extent to which bacterial tree infections weaken the wood must also be considered.

California black oak and southern lowland oaks are notoriously difficult to dry without defects. Ward and Shedd (17) found many of the kiln-drying defects in black oak lumber from Northern California could be traced to bacterial tree infections. Overcup oak and several species of southern red oaks growing on poorly drained bottomlands are often heavily infected with anaerobic bacteria, while oaks growing in the adjacent better drained uplands are more likely to have healthy heartwood (J.C. Ward, unpublished work).

## Other Investigations

Many kiln operators have been unable to successfully kiln dry green lumber from southern lowland oaks and California black oak. Consequently, common industrial practice is to first air dry green lumber from these species to at least 30 percent MC and preferably 20 percent. The air-dried stock can then be kiln dried under a conventional schedule with good results, providing the air-drying conditions were mild. Kiln-drying experiments with a species such as California black oak are

concerned with reducing drying times from the green condition while avoiding the degrade.

Ellwood (4,5) was quite successful with kiln drying 4/4 California black oak green from the saw by using a schedule he designed from an analysis of drying stresses similar to that described by McMillen (7) and Reitz (14). However, when this schedule was employed by Ward and Shedd (17) to dry a green charge of 4/4 California black oak that was heavily infected by anaerobic bacteria, 52 percent of the charge was degraded because of excessive collapse and checking.

Low-temperature forced-air drying has been intensively investigated as a compromise solution to the problem of shortening the time required to air dry green oak lumber. Cobler (1) found that accelerating the air drying of southern oaks by forced-air circulation will give trouble if the humidity cannot be controlled. By controlling the humidity and keeping dry-bulb temperatures under 100° F, Smith (15) was able to successfully reduce the required initial air-drying period for California black oak by about 4 weeks. Gatslick (6) dried 8/4 northern red oak from green to 20 percent MC in 19 days and 9/4 in 55 days in a forced-air dryer that had temperature and humidity controls.

D. G. Cuppett<sup>3</sup> was able to dry 4/4 southern swamp red oak from green to 6 percent MC in 53 days with good quality results. Cuppett used a

<sup>1</sup> Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

<sup>2</sup> Underlined numbers in parentheses refer to literature cited at end of report.

<sup>3</sup> Personal communication from Cuppett at the Northeast Forest Experiment Station, Princeton, W. Va.

combination of forced-air drying followed by conventional kiln drying. A matched sample of the same lumber required a total drying time of 109 days (green to 6 pct MC) when dried by a combination of conventional air drying and kiln drying. Forced-air drying times for the southern swamp red oak were significantly longer than the forced-air drying times for 4/4 Appalachian red oak reported by Cuppett and Craft (3).

## EXPERIMENTAL

### General Procedure

In the first phase of this study, six different drying procedures were screened to determine an optimum method for drying bacterially infected red oak. The screening phase utilized 29- to 30-in.-long sections crosscut from 8- to 12-ft boards for experimental drying samples. Other boards, also 8 to 12 ft long, were dried in the second phase of the study.

The second phase employed a combined procedure of forced-air drying and kiln drying that was judged to be most successful from the results of the screening phase.

### Sample Material

Drying samples used in both phases of the study were taken from 600 bd ft of normal, rough 4/4 northern red oak (*Quercus rubra* L.) lumber and a like amount of rancid, bacterially infected red oak lumber. The material came from winter-cut trees and was collected at two sawmills, one in Wisconsin and one in Illinois. Before the lumber was collected, logs suspected of being bacterially infected were marked on the log yard so that they could be followed through the sawmill and related to sample boards on the green chain. Identification of logs with bacterially infected heartwood was based on the recommendations of Ward et al. (18) where the presence of shake is a principal criterion. At the time of selection, infected logs at Mill Source A generally contained more extensive and advanced stages of bacterial infection than infected logs at Source B. Heavily infected logs will contain rancid heartwood that extends almost to the sapwood and emits strong, rancid, goat-type odors. Oak heartwood with early types of infection will generally emit strong vinegar-type odors (17,18). Both mill locations had ample supplies of logs with normal, healthy heartwood.

Sample boards were selected at the

green chain where infected material from infected logs, and normal material from healthy logs, were stacked in separate piles. Logs preselected as infected often yielded boards with a mixture of normal and infected heartwood, so boards judged to have 30 percent or less of normal heartwood were placed in the infected material piles. For many boards with mixtures of heartwood, it was difficult to judge the amount of infected heartwood on the basis of odor because of freezing winter conditions at both mills. Normal and infected wood designations had to be changed sometimes after the green lumber thawed. About 35 percent of the infected material at each mill graded as Select and Better lumber.

The lumber samples were trucked to the Forest Products Laboratory in covered piles and then each pile was wrapped in polyethylene film and stored at 36° F.

### Screening Tests

This initial phase involved two approaches: (1) kiln drying directly from the green condition and (2) kiln drying after preliminary forced-air drying. Six drying procedures were used, three in each approach. The screening tests are outlined in table 1 together with the number of normal and infected samples used in each procedure.

#### Drying Samples

The samples listed in table 1 were cut from relatively clear sections of 120 boards. Individual drying samples measured 29 to 30 in. in length with widths that ranged from 6 to 10 in. The average green thickness of samples

from Mill Source A was 1-3/16 in. and from Source B 1-1/8 in. During sample preparation, matched wood sections were taken for comparative evaluation of green wood MC, growth rate, specific gravity, and type of bacterial infection. The type of bacterial infection was based largely on odor where the presence of rancid (butyric and valeric acids) and goat (caproic acid) odors indicated advanced or severe bacterial infections. Strong vinegar (acetic acid) odors usually indicated early or less severe bacterial infections. The majority of samples were all heartwood, but a few samples, particularly those designated as normal, contained small areas of sapwood. Each group of samples was wrapped separately in polyethylene film and stored at 36° F. A small tray of paradichlorobenzene crystals was used within each package to inhibit mold, but some mold did occur on sapwood.

When starting an experimental drying run, the appropriate groups were removed from cold storage and warmed to 80° F. A 6- by 12.5-in. zone for surface check measurement was laid out on a clear, flat-grain portion of each face of each specimen (fig. 1). In this zone of each specimen, four lines were drawn to indicate where to crosscut the piece so as to measure honeycombing (internal checking). One of these lines was extended to the full width for shrinkage measurements. Each specimen was end coated with two coats of fast-drying chlorinated rubber coating. After thickness and width was measured, each specimen was stickered in the rack in the drying chamber (fig. 2). The material was kept

Table 1. — Experimental drying procedures and number of sample board sections (29-30 in. long) used for the screening phase of the study

Symbol	Description with initial dry-bulb (DB) and wet-bulb (WB) temperatures	Kiln fan operation	Number of samples
KILN DRYING GREEN FROM THE SAW			
KD-STD	Modification of standard kiln schedule T4-D2 from Rasmussen (13) DB = 110° F, WB = 106° F	Continuous 24 hours	60
KD-I	Mild kiln schedule No. 1 DB = 104° F, WB = 100° F	Continuous 24 hours	60
KD-II	Mild kiln schedule No. 2 DB = 105° F, WB = 102° F	Intermittent 12 hours for first 11 days	60
LOW-TEMPERATURE, FORCED-AIR DRYING PLUS KILN DRYING			
FA-I(25)	Forced-air schedule No. 1 to 25 percent MC (DB = 85° F, WB = 78° F) followed by mild kiln schedule KD-I	Continuous 24 hours	60
FA-IK(20)	Forced-air schedule No. 2 to 20 percent MC (DB = 80° - 82° F, WB = 75° - 77° F) followed by mild kiln schedule KD-II	Intermittent 12 hours for first 11 days	60
FA-IK(25)	Above forced-air schedule No. 2 to 25 percent MC followed by mild kiln schedule KD-II	do	60
Total samples			360



from drying from the time of original sawing until shortly before the run started.

#### Drying Methods

For kiln drying green boards, we used three experimental procedures with a modified form of hardwood kiln schedule T4-D2 (13) as a control schedule. This control schedule, KD-STD, has been used extensively by industry for normal, upland red oak and has proven satisfactory in regard to drying time and quality. The modification is common for high-MC stock and consists of making the first two changes in equilibrium moisture content (EMC) at higher than prescribed wood moisture levels. Mild kiln schedules KD-I and KD-II were modifications of hardwood kiln schedule T2-C1 (12). Schedule T2-C1 is recommended for kiln drying southern lowland oak green from the saw (13). Mild schedule KD-I has a lower initial dry-bulb temperature than KD-STD but approximately the same EMC values. After 48 percent MC was reached, EMC's were lowered fast to avoid increasing total kiln time greatly. A 160° F dry-bulb temperature was used at 15 percent MC to lessen chance of honeycombing. Mild schedule KD-II was devised to reduce excessive honeycombing that occurred when mild schedule KD-I was used. In mild schedule KD-II, the early portion was longer and milder, and the middle portion was lower in temperature than for schedule KD-I.

The first forced-air drying procedure, FA-I(25), was an attempt to follow the procedure for 4/4 red oak described in (2), using a 17 percent EMC and a dry-bulb temperature of 75° to 85° F. Equipment limitations resulted in only a 13 percent EMC being attained while temperature remained at 85° F. When the seven wettest specimens from Source A reached 25 percent MC, conditions were changed to those of kiln schedule KD-I at the 25 percent MC level. Excessive surface checking and honeycombing occurred with FA-I(25), so the second and third forced-air procedures, FA-II(20) and FA-II(25), were designed according to Cuppett and Craft's procedure (2) for 8/4 oak. The rationale was that 8/4 oak is more difficult to dry than 4/4 oak; commercially, infected 4/4 boards could be included in a dryer charge of 8/4 noninfected oak if the experiment showed that such conditions would be satisfactory. Kiln schedule KD-II was used at levels of 20 percent MC for the

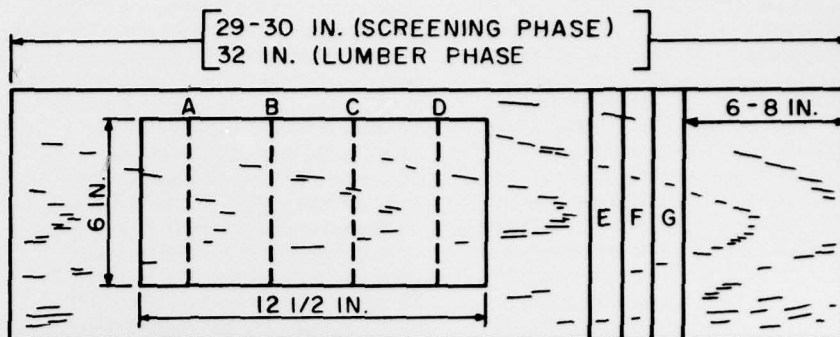


Figure 1.—Schematic showing layout of study measurement zones on the surface of drying samples for the screening phase and kiln samples for the second phase with 8- to 12-ft boards:

A, B, C, D—Cross-section sawing lines to measure honeycomb for both study phases.

E, F, G—One-inch-wide sections for measuring final MC's (av. and shell + core), and stress relief for both phases.

(Key: Surface checks measured in 6- by 12.5-in. area for screening phase only.)

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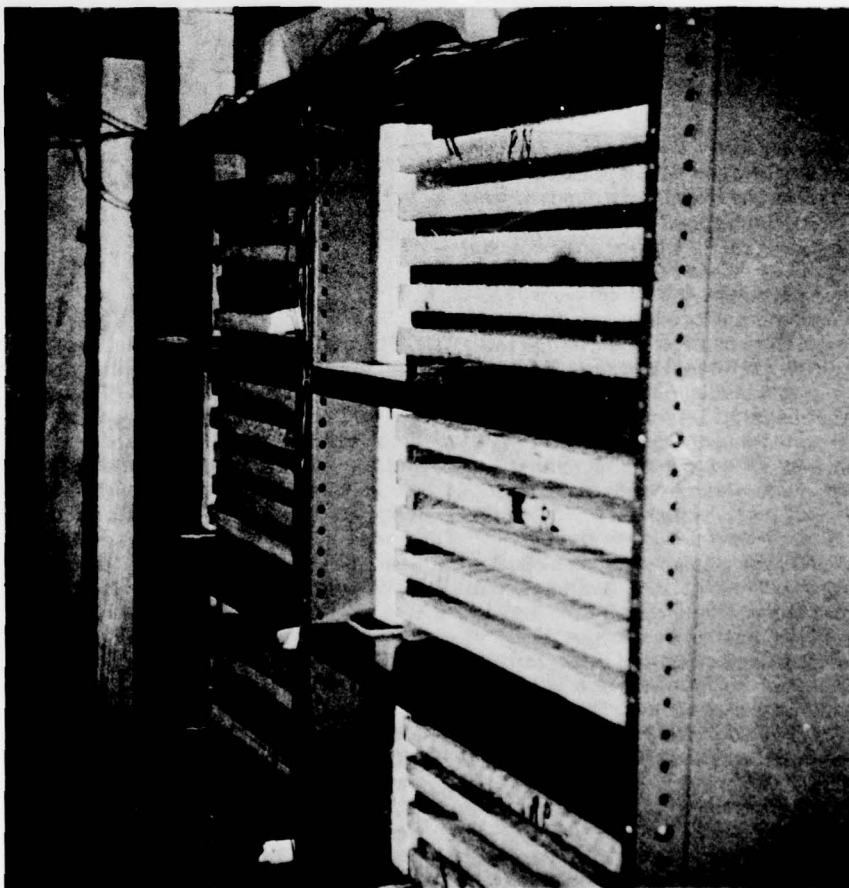


Figure 2.—Method of exposure in dry kiln for sample board sections in the screening phase of the study.

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second forced-air tests, and 25 percent MC for the third tests.

The average air velocities over the specimens were kept uniform by manipulating air bypasses in the main kiln baffle, using small end baffles on some shelves, and employing a balanced design of specimen placement. With both continuous and intermittent fan operation, air velocities across the drying samples averaged about 330 ft/min for kiln procedures KD-STD and KD-II, and about 290 ft/min for KD-I. Average air velocity with continuous fan use throughout the first forced-air procedure, FA-I(25), was 415 ft/min. With intermittent fan use during the first 3 days for FA-II(20), the average air velocity was about 300 ft/min and thereafter was 180 ft/min. Air velocity was kept at 180 ft/min for both intermittent and continuous fan use for FA-II(25). Air circulation was reversed every 6 hours.

Equalizing of MC in the samples was started when the driest specimen reached 4 percent MC and was carried out using a 4 percent EMC. Conditioning started when the wettest specimen was 6 to 7 percent MC and was carried out with an 11 percent EMC.

#### Measurements

At 2- to 5-day intervals, small groups of specimens were briefly removed from the kiln. Each specimen was weighed and examined for surface checking and ring failure. While one specimen was being examined, the others were protected from moisture loss and temperature change. The average MC of the seven wettest specimens in each group was plotted on semilogarithmic graph paper to predict when the next kiln condition change would be reached. All kiln condition changes were made within 5 hours of the time dictated by the schedule.

Width of both the green and dry material was measured to the closest 0.02 in. with a steel rule. Average green thickness was determined from similar measurements on both edges. Final thickness was measured by micrometer calipers at the thinnest place along the width measurement line. The effect of drying conditions and type of heartwood on shrinkage was evaluated on the basis of transverse shrinkage or the combined shrinkage in thickness and width.

The cumulative length of surface checks 0.50 in. or more in length was measured with a steel rule in the designated zone (outlined on the flattest

grain portion of both surfaces of each sample board). The total surface area of the two zones was 150 in.<sup>2</sup>. Depth of the deepest surface checks was measured to the closest 0.02 in., using a probe 0.015 by 0.052 in. wide at the tip.

The width and length of areas that would be unusable because of ring failure, heart shake, and split were measured to the closest 1/4 in. in the 12.5-in. length of the surface check zone, but considering the full width of the specimen. The maximum width of each ring failure was multiplied by its maximum length.

Observations during the final cross-sectional examination sometimes resulted in increases of ring failure dimensions. The shake or splits existing in a few of the green specimens were marked and not included in areas lost because of drying operations. Although surface and internal checks often occurred in ring failure zones, these checks were not included in the evaluation of ring failure defects.

The lengths of honeycomb checks were measured from the four sections crosscut from the samples to the nearest 0.02 in. and the cumulative total reduced to honeycombing per 10 inch of width. In most cases, honeycomb checks were open and easily measurable, but a few barely visible checks extending down from the surface were included in honeycombing.

#### Lumber Drying Test

The remainder of the rough green lumber not used for the screening tests was dried in an experimental FPL dry kiln for this phase of the study. During the 4 months between tests, the boards were wrapped in polyethylene and stored at 36° F. Ninety boards, 8 to 12 ft long, were stacked in a 4-ft-wide kiln charge on 3/4-in. stickers spaced 16 in. apart. Fourteen kiln samples, 32 in. long, were used to determine moisture loss during drying. About half of the lumber volume and 12 kiln samples contained bacterially infected heartwood.

The drying procedure used was similar to the forced-air procedure, FA-II(25), used in the screening tests, but was modified to terminate forced-air drying at 23 percent MC rather than 25 percent. It was assumed the interior boards in the pile would be slightly wetter than the kiln samples on the edge. Kiln fans were run between 8 a.m. and 8 p.m. daily for the first 11 days,

after which fans were operated continuously. Air velocity averaged 200 ft/min during the entire run and uniformity across the load was achieved by baffling. Fan reversal was changed from 6 to 3 hours.

For evaluation purposes, the boards were divided into two groups: (1) The 14 kiln sample boards and (2) the uncut lumber. Each of the 14 kiln sample boards was marked off according to the method outlined for the 30-in. drying samples used in the screening tests (fig. 1). The kiln samples were measured for shrinkage and drying defects by the same methods used in the screening tests. Before drying, all full-length boards were examined for checks and splits and measured for thickness and width. After drying, these boards were measured for shrinkage, surface checks, and end splits in the rough state. Then the boards were twice surfaced on two sides; first to 7/8 in. thick and then to 3/4 in. thick. Presence of honeycomb and ring failure was determined on the basis of open internal checks appearing on the surfaced faces of the boards.

## RESULTS AND DISCUSSION

### Wood Quality Factors

Some characteristics of heartwood for the red oak used in this study are listed in table 2. The average green MC content values of infected wood from Source A are higher than the average green MC of normal wood and compare favorably with values from other studies and observations in industry. The material from Source B is an exception to the general rule, as the green MC of normal heartwood averaged higher than the MC of infected heartwood. Both normal and infected heartwood from Source B had higher average MC values than are generally observed for normal green oak heartwood.

Although Source B material had higher green MC values, less advanced or heavily infected rancid heartwood was present than in the infected material from Source A. The advanced type of bacterial infection observed in Source A material could be related to a tendency of the heartwood to develop deep surface checks and honeycomb during the early and middle stages of drying under both conventional and forced-air drying procedures. These data suggest that presence of such volatile fatty acids as butyric, valeric, and caproic acids better indicate defect-prone oak heartwood than do



green MC values averaging above 85 percent.

The specific gravity of heartwood from Source A was higher than for Source B. These higher specific gravity values can be related to the faster rates of growth for the B material. The presence of bacterial infections could not be related to a lowering of specific gravity for study material from either source.

### Drying Conditions and Rates

Drying conditions are listed in table 3 for the three kiln procedures, in table 4 for the three combined forced-air plus kiln procedures, and in table 5 for the full-sized lumber phase. Similarly,

drying curves and times are shown in figures 3, 4, and 5 for each group of drying procedures.

Changes in drying conditions were based on the average MC of the seven wettest infected specimens from Source A. This group was the slowest drying of the four groups in each run. Generally, the other groups in each run had slightly milder kiln conditions than the infected material from Source A after the first step of each schedule.

Surface checking and honeycombing were the basis for judging the six drying procedures in the screening phase of the study. High EMC's and low air velocities in the early stages of drying help to limit surface checking in

infected wood. Red oak with advanced bacterial infection is subject to excessive honeycombing even with the moderate temperatures of experimental kiln schedule KD-I. Under the kiln drying conditions of KD-STD, honeycombing and considerable darkening of the wood occurred in the infected material. Forty percent or more of the infected Source A specimens dried by KD-STD, KD-I, and FA-I(25) had measurable internal checking or honeycombing. This defect can be controlled by withholding use of higher temperatures until internal MC values are below the fiber saturation point (8,14). Less honeycomb and greater brightness was attained in infected wood dried by forced-air procedures FA-II(20) and FA-II(25).

All procedures were generally satisfactory for infected Source B material. Total drying times shown include equalization to about 5 percent average MC and conditioning for 14 to 17 hours. The total time of 32 days for schedule KD-STD was slightly longer than the 26 to 28 days generally required commercially for normal red oak of this density and thickness. Schedule KD-I required only 2 days longer than KD-STD. Although schedule KD-I was very mild at the start, conditions were made more severe than those of KD-STD in the intermediate part of the schedule. Schedule KD-II was considerably less severe than KD-STD and took 9 days longer.

The first forced-air procedure FA-I(25) took 37 days. Although this was

Table 2. - Characteristics of normal and bacterially infected northern red oak used in this study

Source	Moisture content of green heartwood			Growth rate rings per inch <sup>1</sup>	Specific gravity oven-dry weight and green volume		Infection type <sup>2</sup>		
	Range				Mean	Range	Early	Advanced	
	Mean	Minimum	Maximum						
	Pct	Pct	Pct			Min	Max	Pct	Pct
NORMAL HEARTWOOD									
A	80.0	64.1	- 96.9	9.7	0.576	0.444	- 0.736	-	-
B	93.7	67.5	- 108.9	11.8	.540	.494	- .595	-	-
INFECTED HEARTWOOD									
A	86.2	68.7	- 105.9	10.6	.568	.489	- .632	29	71
B	89.3	56.1	- 103.4	11.0	.553	.503	- .614	75	25

<sup>1</sup>On cross sections of specimens after drying.

<sup>2</sup>Estimated as a percent of total samples with infected heartwood from each source. Early infection indicated by wood with strong vinegar or acetic acid odors while advanced infections indicated by rancid and goat odors of butyric, valeric, and caproic acids.

Table 3. - Drying conditions for kiln drying of green 4/4 northern red oak samples in the screening phase of the study

KD-STD, modified kiln schedule T4-D2				KD-I				KD-II			
Control MC <sup>1</sup>	Temperature, Dry-bulb Wet-bulb		EMC	Control MC <sup>1</sup>	Temperature, Dry-bulb Wet-bulb		EMC	Control MC <sup>1</sup>	Temperature, Dry-bulb Wet-bulb		EMC
Pct	°F	°F	Pct	Pct	°F	°F	Pct	Pct	°F	°F	Pct
Green	110	106	18	Green	104	100	17.5	Green	105	102	18.5
54	110	105.5	17	58	105	100	16	51	106	102	17.5
-	-	-	-	48	105	96.5	13	46	106	100	15
42	110	101.5	13	40	110	93.5	9	40	106	97.5	13
35	110	96	10	34	115	84	5	35	110	92	8.5
30	120	88	5	30	120	79	3	30	115	84	5
25	130	80	2	25	130	85	3	25	120	86	4.5
21	140	90	2.5	20	140	92.5	3	20	130	91	4
15	180	129	3	15	160	110	3	16	150	95	2
11	180	145	5	11	180	136	4	11	170	119	3
9	180	137	4	-	-	-	-	-	-	-	-
EQUALIZING											
8	175	131	4	8	170	122.5	3.5	10	170	130	4.5
CONDITIONING <sup>2</sup>											
7	180	171.5	12	6	176	166	11	6	175	165	11

<sup>1</sup>Average MC of 7 wettest specimens of material from Source A.

<sup>2</sup>Conditioning times approximately 14 to 17 h.

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Table 4. — Drying conditions for forced-air drying followed by kiln drying of green 4/4 northern red oak samples in the screening phase of the study

FA-II(25), forced-air dried to 25 percent MC followed by kiln schedule KD-I				FA-II(20), forced-air dried to 20 percent MC followed by kiln schedule KD-II				FA-II(25), forced-air dried to 25 percent MC followed by kiln schedule KD-II			
Control MC <sup>1</sup>	Temperature		EMC	Control MC <sup>1</sup>	Temperature		EMC	Control MC <sup>1</sup>	Temperature		EMC
Pct	Dry-bulb °F	Wet-bulb °F	Pct	Pct	Dry-bulb °F	Wet-bulb °F	Pct	Pct	Dry-bulb °F	Wet-bulb °F	Pct
FORCED-AIR											
Green	85	78	13.5	Green	81	76	16	Green	82	77	15.5
—	—	—	—	52	82	76.5	15	53	83	78	15.5
—	—	—	—	—	—	—	—	50	83	77	14.5
45	95	70	25.3	341	90	73	28	440	90	75.5	29
KILN											
25	130	85	3	—	—	—	—	25	120	85	4.5
22	140	92.5	3	20	130	85	3	20	130	85	3
14	160	110	3	14	147	102	3.5	15	150	100	3
12	177	133	4	11	169	118	3	11	170	119	3
EQUALIZING											
8	170	126	4	10	169	130	4.5	8	170	126	4
CONDITIONING <sup>5</sup>											
6	176	166	11	7	175	165	11	7	175	165	11

<sup>1</sup>Average MC of 7 wettest infected specimens of material from Source A.

<sup>2</sup>Approximate EMC; wet-bulb temperature not controlled.

<sup>3</sup>Each group other than infected A was removed to wrapped storage when its controlling MC approached 20 pct. When infected A group reached 20 MC, all groups were kiln dried together.

<sup>4</sup>Handled in same manner as groups in footnote 3, but at the 25 pct MC level.

<sup>5</sup>Conditioning times approximately 14 to 17 h.

only 5 days longer than the control, drying conditions were too severe. Forced-air procedure FA-II(20) was very conservative. Total time was 52 days. Using forced-air procedure FA-II(25) reduced drying time to 43 days. When a kiln charge of full-sized lumber was dried by forced-air procedure FA-II(23), similar to FA-II(20) and FA-II(25), total drying time was extended to 58 days (fig. 5).

There was no practical difference in final MC or drying stress relief among drying procedures, sources, or types of material. Final MC average between 6.0 and 7.6 percent, except for 7.8 percent for both normal and infected material from Source A dried by KD-STD. Minimum MC values for all specimens were 5.6 percent, and all specimens were fully relieved of stress ("casehardening") except three dried by KD-STD, two of the screening forced-air runs FA-II(20) and FA-II(25), and one of the final forced-air run FA-II(23). The treatments were considered entirely satisfactory and not conducive to honeycombing of infected material.

## Shrinkage

Average shrinkage values for all samples dried in this study are listed in table 6. Shrinkage of the heartwood from Source A was greater than shrinkage of material from Source B

Table 5. — Drying conditions and times for a mixed charge of 4/4 northern red oak lumber with normal and bacterially infected heartwood dried by a combination of low-temperature, forced-air, and conventional kiln drying procedures

Moisture content range for each temperature step <sup>1</sup>	Kiln temperatures		Equilibrium moisture content	Drying time for each MC-temperature step
	Dry-bulb	Wet-bulb		
Pct	°F	°F	Pct	Days
LOW-TEMPERATURE, FORCED-AIR <sup>2</sup>				
Green to 60	80	77	18.7	20 - 11
60 to 53	82	78	17.1	11 - 15
53 to 48	83	78	15.6	15 - 19
48 to 40	83	77	14.4	19 - 24
40 to 23	389-90	370-75	6.8 - 9.3	24 - 39
KILN DRYING				
23 to 20	120	88	5.0	39 - 41
20 to 15	128	100	6.1	41 - 46
15 to 11	148	103	3.6	46 - 54
EQUALIZING <sup>4</sup>				
11 to 5	169	127	4.1	54 - 57
CONDITIONING				
5 to 7	178	166	10.2	57 - 58

<sup>1</sup>Average MC of 5 wettest kiln samples used to control step change.

<sup>2</sup>From start of drying to 11 days, fans were used only between 8 a.m. and 8 p.m. with 3-h reversal. Continuous 24-h fan operation after 11 days with 3-h reversal.

<sup>3</sup>No control of wet-bulb unless EMC conditions drop below 6.8 pct.

<sup>4</sup>Equalizing started when driest sample reached 4 pct MC.

<sup>5</sup>Total conditioning time was 15 h.



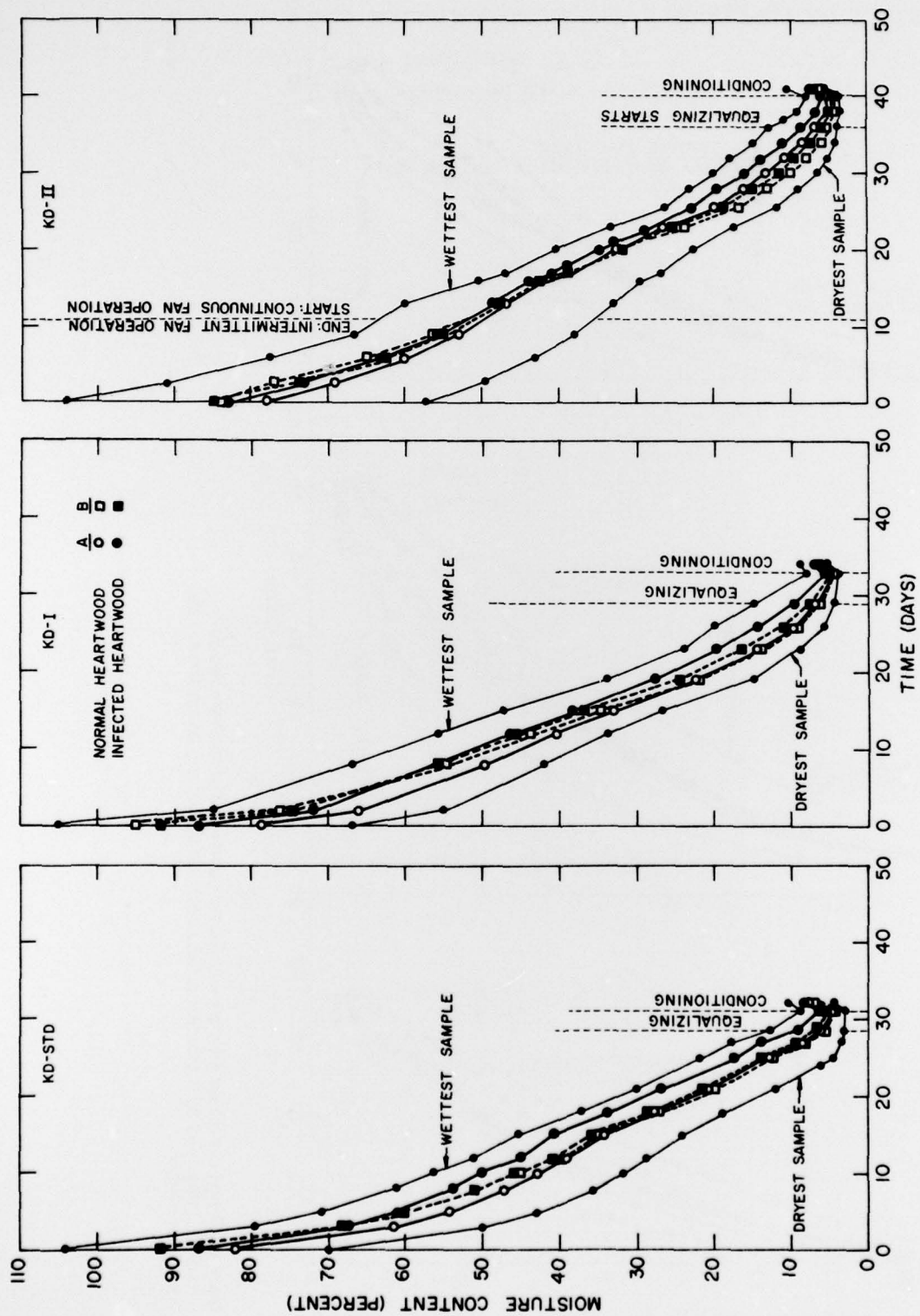


Figure 3.—Drying curves for normal and infected heartwood of northern red oak board samples kiln dried in the screening phase.

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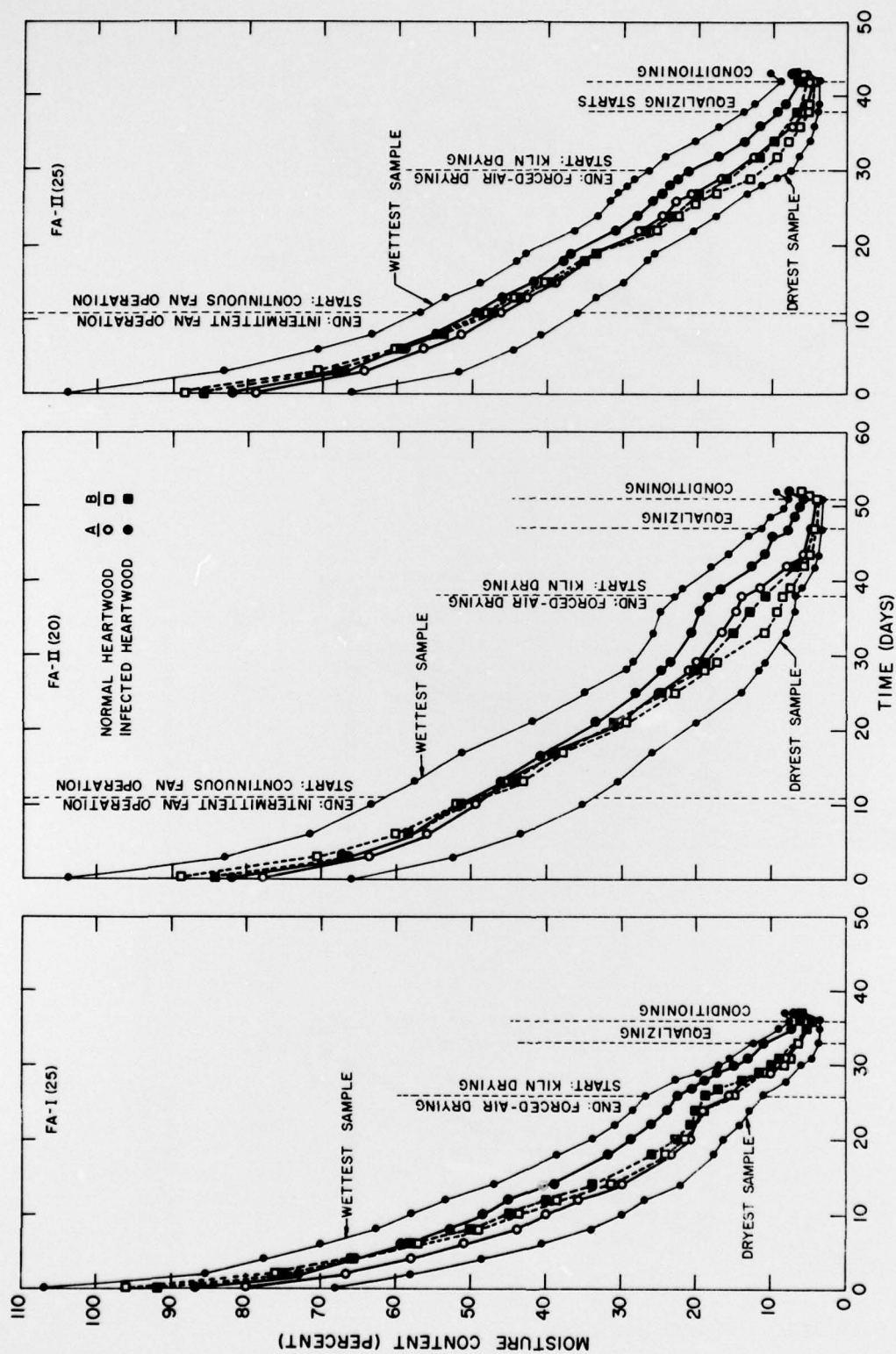


Figure 4.—Drying curves for normal and infected heartwood of northern red oak board samples dried by combination forced-air and kiln-drying procedures in the screening phase.

U.S. Forest Products Laboratory.

Drying procedures for bacterially infected northern red oak lumber; by John M. McMillen, James C. Ward, and Joseph Chern. Madison, Wis., FPL.

16 p. (USDA For. Serv. Res. Pap. FPL 345.)

Describes a procedure for drying green 4/4 northern red oak lumber that contains heartwood infected with bacteria. Such lumber may develop serious honeycomb, surface checks, and ring failure during drying. This material should be dried by first a low-temperature, forced-air schedule, and then kiln dried to 6 to 8 percent moisture content with a mild kiln schedule.

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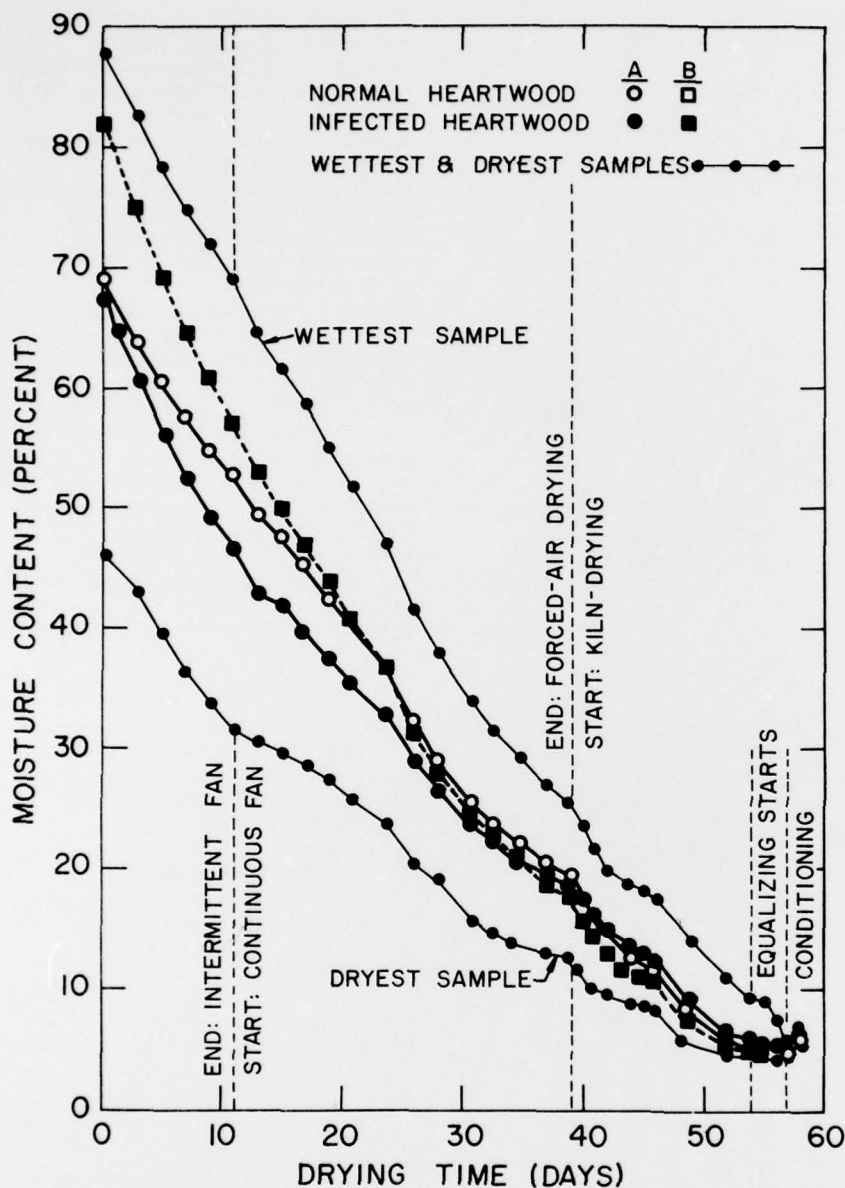


Figure 5.—Drying curves for normal and infected heartwood of northern red oak in the full-size lumber phase.

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and can be partly explained by the higher specific gravity of the A material. Factors other than specific gravity are evident in table 6 and need to be considered with respect to shrinkage of oak.

Table 6 shows that in this study infected heartwood shrinks more than normal heartwood. Also, infected heartwood tends to shrink more when kiln-dried green than when first dried by low-temperature, forced-air procedures.

These observations agreed with other studies where kiln-dried and bacterially infected heartwood of eastern red oaks (J. C. Ward, unpublished) and California black oak (17) shrinks more than air-dried and normal heartwood.

The general explanation for differences in shrinkage (given similar specific gravity and growth ring orientation) is that pieces with greater shrinkage developed greater compression set during drying.

Compression set develops in the interior of boards during the intermediate stages of drying when the MC of the core is still above the fiber saturation point. The higher temperatures of kiln drying will cause greater compression set with significantly greater shrinkage than the lower temperatures of air drying (8). A possible explanation for shrinkage differences between normal and infected heartwood is that infected wood is weaker in compressive strength.

Figure 6 shows that during the course of drying the core of infected heartwood being kiln dried will be wetter at a given average MC than the core of infected heartwood being forced-air dried. At the same average MC, the cores of both normal and infected heartwood being air dried will have about the same inner MC's. Yet, infected heartwood that is forced-air dried shrank more than forced-air dried normal heartwood. Although not shown in figure 6, the core MC of kiln-dried normal heartwood is less than the core MC of infected heartwood at the same average MC and close to the core MC of the air-dried material. It does not appear that differences in core MC under different drying procedures contributes as much to magnitude of shrinkage as do drying temperatures and compressive strength of the wood.

### Surface Checking

Infected heartwood has a greater tendency to surface check under all drying procedures (table 7). The tendency to surface check cannot be completely blamed on bacterial infections, and such wood quality factors as specific gravity and growth ring orientation must be considered also. Boards from Source A with both normal and infected heartwood checked more than comparable material from Source B, and this can be attributed to differences in growth rate and specific gravity. Flat-sawn boards with normal heartwood were more likely to surface check than quarter-sawn and bastard-sawn boards with infected heartwood. However, a quarter-sawn board with infected heartwood is prone to develop honeycomb, whereas a flat-sawn board with normal heartwood does not develop honeycomb even after surface checking more.

Bacterial infection does contribute to increased severity of surface checking although it is not the sole factor involved. The data in table 7 indicate

Table 6. — Shrinkage of northern red oak from green to 6 to 8 percent moisture content.<sup>1</sup> According to type of heartwood and drying procedure

Study phase	Drying procedure	Shrinkage loss (Pct of green dimensions)	
		Source A Transverse	Source B Transverse
		Pct	Pct
	NORMAL HEARTWOOD		
Screening	Kiln dried, green		
	KD-STD	12.55	11.11
	KD-I	13.63	8.06
	KD-II	12.90	9.63
	Total kiln dried	12.93	9.83
	Forced-air plus kiln dry		
	FA-I(25)	10.55	10.30
	FA-II(20)	10.23	9.41
	FA-II(25)	11.13	11.01
	Total forced-air plus kiln dry	10.63	10.32
Lumber	Forced-air plus kiln dry to 23 percent MC	12.02	12.02
Total normal heartwood		11.88	10.37
	INFECTED HEARTWOOD		
Screening	Kiln dried, green		
	KD-STD	14.46	11.91
	KD-I	16.27	14.90
	KD-II	14.94	11.57
	Total kiln dried	15.43	12.90
	Forced-air plus kiln dry		
	FA-I(25)	14.83	13.42
	FA-II(20)	14.68	11.62
	FA-II(25)	15.54	10.67
	Total forced-air plus kiln dry	15.01	11.98
Lumber	Forced-air plus kiln dry to 23 percent MC	13.20	13.78
Total infected heartwood		14.61	12.68

<sup>1</sup> Total boards = 452.

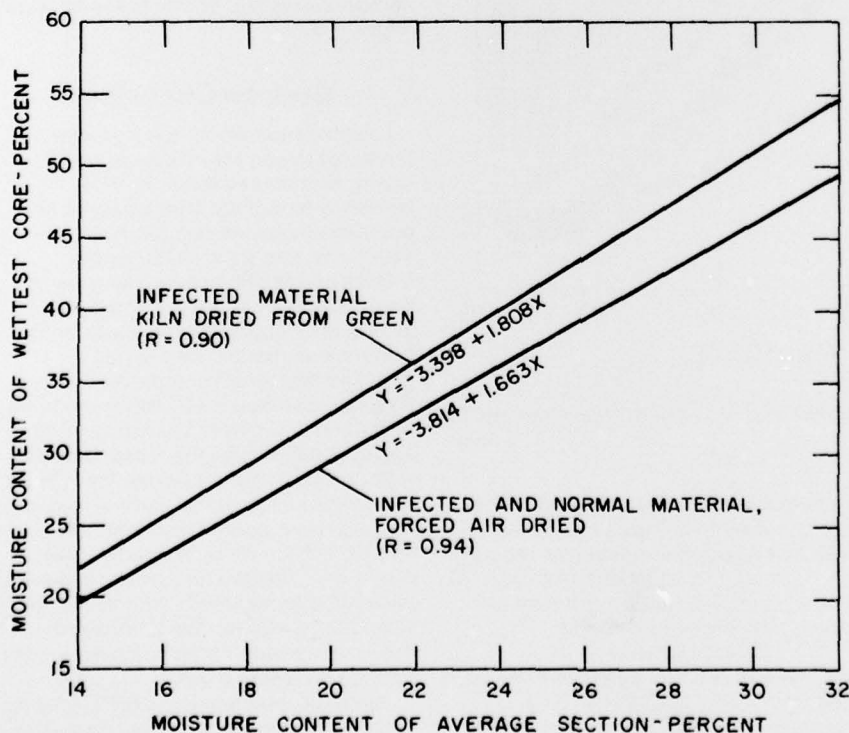


Figure 6. — Core MC as a function of average MC at intermediate MC determinations.

any advantages that might be gained from using forced-air drying for reducing surface checking will not be realized if bacterial heartwood is present. During the early stages of drying, the surface zones of green oak are subjected to very high perpendicular-to-grain stresses (19) and bacterial infections obviously weaken the wood in this direction without necessarily reducing the specific gravity.

Initial surface checking developed by the second to fourth day of drying, and infected heartwood usually started checking earlier than normal heartwood. The MC at the time of last surface check extension was lower for infected heartwood than for noninfected wood. The MC's of infected material from both sources averaged 37 percent at the time of last checking. For normal material surface checking stopped sooner at 52 percent MC as compared to normal Source A material which ceased checking at 44 percent MC. Gatslick (6) found that surface checking in both 4/4- and 9/4-in.-thick red oak stopped at approximately the same MC (45 pct) when dried under low-temperature forced-air conditions. In this study the MC at last checking depended on differences in type of heartwood rather than drying procedures.

Intermittent fan operation is recommended by Cuppett and Craft (2) for forced-air drying batches of oak that tend to surface check more than normal. The fans should be turned off during the day and on only at night. For oak being forced-air dried in installations without humidity control, Cobler (1) found that fans must be turned off when the relative humidity falls below 50 percent. Probably some flattening of the moisture gradient occurs, resulting in lower drying stresses than is possible with full-time fan operation. Use of intermittent air circulation during the early stage of forced-air drying in procedures FA-II(20) and FA-II(23) might provide a partial explanation for low checking values in infected boards. These low checking values compare with those achieved by presurfacing normal red oak (10,11).

### Honeycombing

Honeycomb was always confined to bacterially infected heartwood. Rancid heartwood with advanced stages of infection was much more prone to develop honeycomb than the vinegar-

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type heartwood in earlier stages of infection. Bacterially infected boards from Source A contained proportionally more rancid heartwood and tended to develop more honeycomb than infected boards from Source B.

The occurrence and severity of honeycomb is greatly reduced but not always eliminated with low-temperature, forced-air drying of green oak with infected heartwood (tables 8 and 9). Best results were obtained when infected lumber was forced-air dried to an average MC of 20 percent with procedure FA-II(20). Bacterial heartwood in early stages of infection (Source B) was successfully dried without honeycomb with conventional kiln schedule T4-D2 as shown in figure 7. Comparable reduction of honeycomb in rancid heartwood from Source A was obtained only by mild forced-air drying of green material as shown in figure 8. We assume, from results of previous studies (17,18), that kiln schedules more severe than T4-D2 will cause honeycombing of oak lumber with all types of bacterial heartwood. It is also possible that, with initial kiln temperatures in excess of 140° F, honeycomb will develop even in normal, healthy oak heartwood but this is yet to be studied.

Honeycomb can originate in three ways: Deepening of a surface check followed by closure at the surface (bottle-neck checks); extension of an end check; and spontaneous formation within the board (8). All three varieties of honeycomb were observed in the bacterial heartwood of this study from material dried under what is generally considered mild temperature conditions (table 9). It is well known that the raising of temperatures can cause honeycombing of oak that has been partially air dried to 30 percent MC or above, but when the MC is less than 20 percent, temperatures of 180° F will cause no internal checking even in bacterially infected oak.

We must assume then that bacterially infected oak—especially the rancid type—is intrinsically weaker than normal oak even at the lower drying temperatures. This is supported by the curves in figure 6 showing no significant difference between the core MC of bacterial and normal oak boards when dried under low-temperature, forced-air conditions. In this respect, it is noteworthy that Youngs and Bendtsen (19) found a significant consistency in the location of maximum stress zones in the cross section of red oak boards dried at temperatures of 80°, 110°,

Table 7. — Surface checking in normal and bacterially infected 4/4 northern red oak dried by seven procedures

Procedure	Percent of pieces affected				Length per 100 in. <sup>2</sup>			
	Normal		Infected		Normal		Infected	
	A	B	A	B	A	B	A	B
	Pct	Pct	Pct	Pct	In.	In.	In.	In.
Screening phase <sup>1</sup>								
Kiln dried, green								
KD-STD	47	7	85	38	1.4	0.1	20.0	1.5
KD-I	15	0	76	12	0.2	—	6.6	2
KD-II	0	0	72	12	—	—	9.4	.7
Forced-air plus kiln dried								
FA-I(25)	0	0	71	12	—	—	9.8	1.9
FA-II(20)	0	0	43	12	—	—	3.1	.3
FA-II(25)	33	13	60	7	.9	.1	6.5	.4
Lumber phase <sup>2</sup>								
FA-II(23)	39	21	62	52	2.3	.1	.9	.8

<sup>1</sup>Measured within 2 intensive observation areas (6 by 12½ in.) on each board sample (29.30 in. long).

<sup>2</sup>Measured within 2 intensive observation areas (6 by 12½ in.) on a clear surface zone of each full-length board (8.12 ft long).

Table 8. — Honeycombing in normal and bacterially infected 4/4 northern red oak dried by seven procedures

Procedure	Percent of pieces affected				Length per 10 inch width			
	Normal		Infected		Normal		Infected	
	A	B	A	B	A	B	A	B
	Pct	Pct	Pct	Pct	In.	In.	In.	In.
Screening phase <sup>1</sup>								
Kiln dried, green								
KD-STD	0	0	54	0	—	—	1.11	—
KD-I	0	0	41	0	—	—	1.05	—
KD-II	0	0	23	12	—	—	.71	0.17
Forced-air plus kiln dried								
FA-I(25)	0	0	47	12	—	—	.78	.22
FA-II(20)	0	0	14	0	—	—	.44	—
FA-II(25)	0	0	27	7	—	—	.50	.88
Lumber phase <sup>2</sup>								
FA-II(23)	0	0	25	0	—	—	.68	—

<sup>1</sup>Measured from 4 sections cross-cut from each sample board.

<sup>2</sup>Measured from 4 sections cross-cut from each kiln sample.

Table 9. — Occurrence of honeycomb in full-length boards that were surfaced after forced-air and kiln drying procedure FA-II(23)

Mill source	Total number of boards	Number of affected boards	Honeycomb			
			In usable area of affected boards <sup>1</sup>	Origin of honeycomb <sup>2</sup>		
				Bottle-neck checks	Internal checks	End splits
			Pct	Pct	Pct	Pct
NORMAL						
A	18	15	10	72	0	28
B	15	0	—	—	—	—
INFECTED						
A	24	9	28	39	28	33
B	21	6	17	21	43	36

<sup>1</sup>Percent of surface area (both faces) of board clear cuttings.

<sup>2</sup>Estimated from visual observations and expressed as a percent of total number of observations of honeycomb in each board sort.

<sup>3</sup>Honeycomb occurred only in minor areas of bacterially infected heartwood that were allowed in normal board sorts.

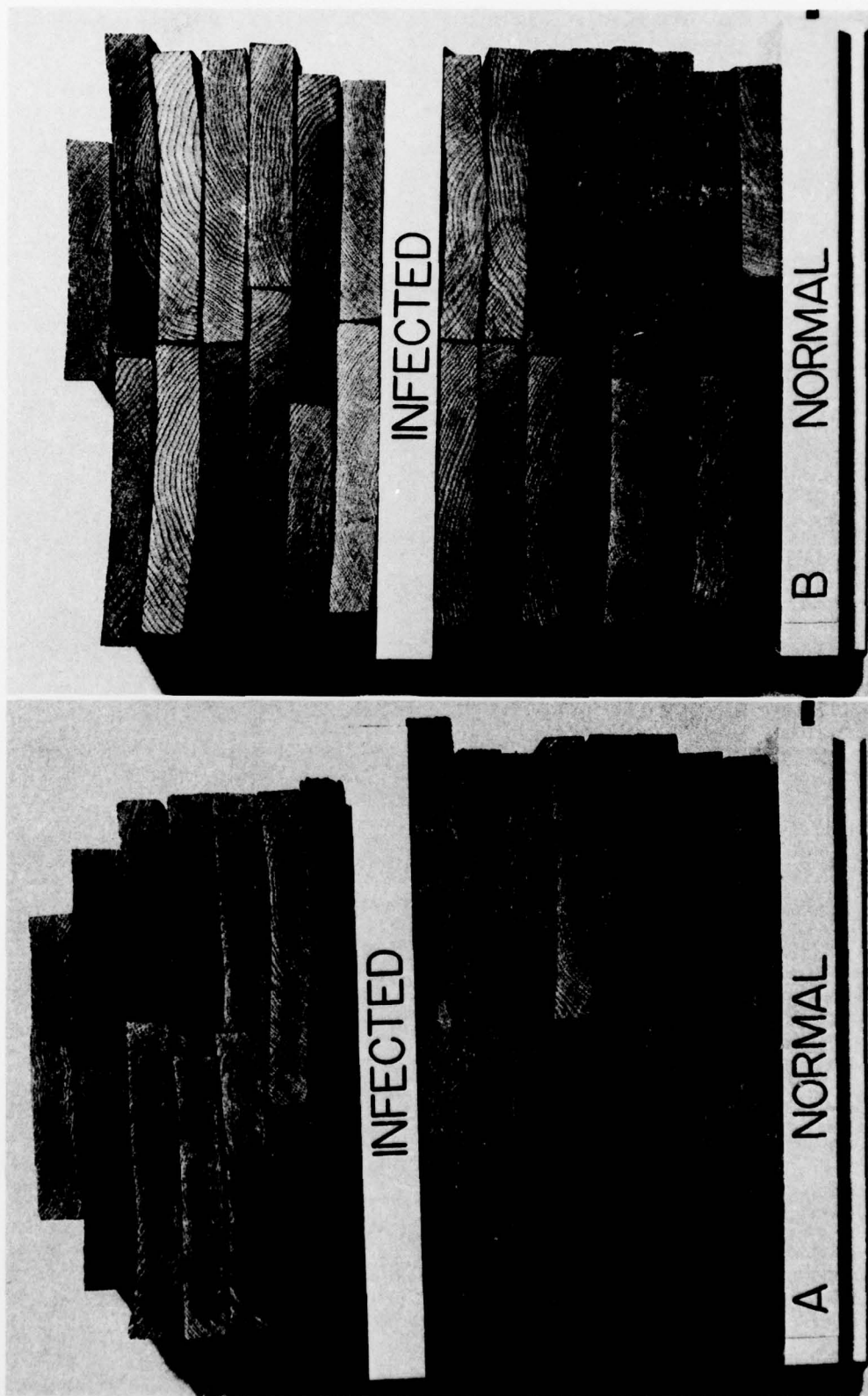


Figure 7.—Cross sections of specimens from Sources A and B kiln dried by T4-D2 schedule (KD-STD), showing honeycomb and some ring failure and some darkening.

(M 145 764-2, M 145 764-3)

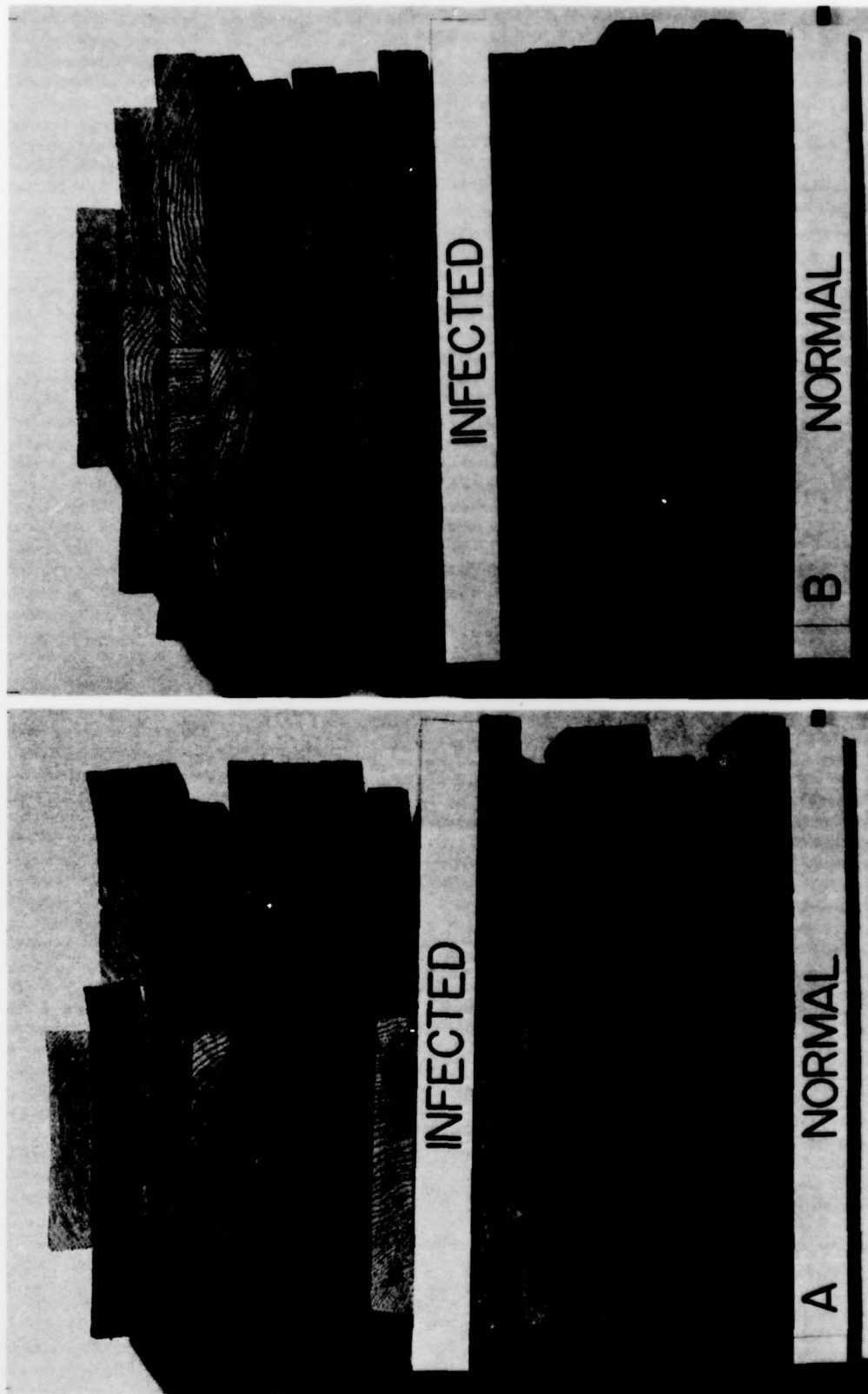


Figure 8.—Cross sections of specimens from Sources A and B dried by second forced-air procedure to 25 percent MC, then kiln dried by schedule KD-II.  
(M 145 764-12, M 145 764-1)



125°, and 140° F. They observed that the consistent location of maximum shearing stress at all temperature levels is coincident with the location of honeycomb and collapse.

### Ring Failure

The occurrence and severity of ring failure is shown in table 10. Ring failure developed only in bacterially infected heartwood, but not in as many specimens as surface checking and honeycomb. On the other hand, the severity of ring failure could not be decreased with mild drying conditions to the extent that honeycomb was decreased. This supports the proposition by Ward et al. (18) that ring failure is an incipient form of ring shake which is first initiated by stresses in the living tree.

### CONCLUSIONS

1. Red oak lumber containing rancid or bacterially infected heartwood should first be dried green from the saw by a low-temperature, forced-air schedule to at least 25 percent MC and preferably 20 percent. The forced-air dried lumber can then be kiln dried to 6 to 8 percent MC with good results by using a milder kiln schedule than normally recommended for air-dried oak.

2. Forced-air and kiln-drying combinations will greatly reduce, but not always eliminate, honeycombing of oak heartwood in the advanced, rancid stages of bacterial infection. Red oak heartwood in early stages of bacterial infection can be kiln dried green under

both mild and conventional kiln (T4-D2) schedule with minimal and sometimes no development of honeycomb.

3. Severity of surface checking is substantially increased by bacterial infections. Low-temperature, forced-air drying is not as effective for reducing surface checking in bacterially infected oak as it is for reducing honeycombing.

4. Bacterially infected oak is subject to surface check extension at lower MC values than normal oak, precluding fast lowering of relative humidity in the intermediate stages of kiln drying.

5. Ring failure was not minimized by using the milder drying conditions of this study as were surface checking and honeycomb. This is because ring failure appears to be an incipient form of ring shake that begins in bacterially infected wood of the living tree.

6. Shrinkage of bacterially infected heartwood is greater than the shrinkage of normal heartwood. Kiln-drying bacterially infected oak from the green condition generally results in greater shrinkage than if the wood was first dried under low-temperature, forced-air conditions.

7. If kiln dried from the green condition, northern red oak in the advanced stages of infection has higher core MC values than forced-air dried normal or infected oak at any specific average MC value between 14 and 32 percent.

8. Satisfactory relief of drying stresses was attained with both normal and bacterially infected wood by equalizing at 1 percent lower MC and EMC than are normally recommended, and then conditioning for 14 to 17 hours at the EMC values usually prescribed.

Table 10. — Ring failure in normal and bacterially infected 4/4 northern red oak dried by seven procedures

Drying procedure	Percent of pieces affected				Area of ring failure per 100 in. <sup>2</sup> of affected usable surface			
	Normal		Infected		Normal		Infected	
	A	B	A	B	A	B	A	B
	Pct	Pct	Pct	Pct	In. <sup>2</sup>	In. <sup>2</sup>	In. <sup>2</sup>	In. <sup>2</sup>
Screening phase								
Kiln dried, green								
KD STD	0	0	31	0	—	—	8.2	—
KD-I	0	0	41	0	—	—	13.1	—
KD-II	0	0	41	12	—	—	11.4	1.6
Forced-air plus kiln dry								
FA-I(25)	0	0	29	6	—	—	7.6	1.4
FA-II(20)	0	0	43	0	—	—	12.3	—
FA-II(25)	0	0	27	7	—	—	8.3	1.2
Lumber phase FA-II(23)								
Kiln samples <sup>1</sup>	0	0	50	25	—	—	6.2	6.2
Boards <sup>2</sup>	<sup>3</sup> 11	<sup>3</sup> 7	42	71	<sup>3</sup> 18.8	<sup>3</sup> 6.7	31.3	17.3

<sup>1</sup>Kiln samples: 32 in. long.

<sup>2</sup>Boards: 8 to 12 ft long.

<sup>3</sup>Present only in minor areas of infected heartwood that were allowed in full-length boards containing mostly normal heartwood.

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